Research Article

Neutrino Mass and the Higgs Portal Dark Matter in the ESSFSM

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We extend the standard model with three right-handed singlet neutrinos and a real singlet scalar. We impose two Z_2 and Z_2' symmetries. We explain the tiny neutrino mass-squared differences with two Z_2- and Z_2'-even right-handed neutrinos using type I seesaw mechanism. The Z_2-odd fermion and the Z_2'-odd scalar can both serve as viable dark matter candidates. We identify new regions in the parameter space which are consistent with relic density of the dark matter from recent direct search experiments LUX-2016 and XENON1T-2017 and LHC data.

1. Introduction

The found Higgs boson at the Large Hadron Collider (LHC) [1–3] completes the search for the particle content of the standard model (SM). The hierarchy problem related to the Higgs boson mass has motivated a plethora of models such as supersymmetry, and extra dimensions in which the fine-tuning is reconsidered. However, an inevitable consequence of these models is that the new physics should lie close to the TeV scale. Nonobservations [4] of any new physics from the collider experiments imply that the Higgs hierarchy issue is reverting back to being an unsolved open problem.

In addition, the SM is unable to explain some physical phenomena in nature such as the existence of massive neutrinos, the presence of dark matter (DM), the observed matter-antimatter asymmetry, and so forth. In the SM, by construction, the neutrinos are massless as it does not include right-handed neutrinos. However, from the neutrino oscillation experiments, we got convinced that at least two neutrinos have nonzero mass. The neutrino oscillation experiments have given information about the mass-squared differences between neutrino mass eigenstates. However the individual value of the masses is not yet known. It has been seen that the sum of the three neutrino masses is less than ~0.1 eV [5–7] which is consistent with the cosmological measurements. Individual masses and the basic nature of neutrinos, that is,

whether they are Dirac or Majorana particles, are still an open question.

As neutrino masses are very tiny compared to the other fermion masses, it is believed that the mechanism behind neutrino mass generation is different from the other fermions. The other fermions are obtained mass through the Higgs mechanism. The most popular natural explanation of small neutrino masses is the seesaw mechanism. There are broadly three classes of such models, namely, type I, type II, and type III seesaw models requiring involvement of right-handed neutrinos, a $SU(2)_L$ triplet scalar with hypercharge $Y = 2$ and $SU(2)_L$ hyperchargeless triplet fermions, respectively. The minimal scenario in this respect is the canonical type I seesaw mechanism, in which the SM is extended by a right-handed Majorana neutrinos [8–14]. The TeV-scale seesaw mechanism has been discussed in [15–17]. Including extra scalar fields, it has been studied in [18–21].

Various kinds of astrophysical observations, such as anomalies in the galactic rotation curves, gravitational lensing effects in the Bullet cluster, and excess gamma rays (The excess gamma rays from the galactic centers may come from other sources like pulsars.) from the galactic centers, have indicated the existence of DM in the Universe. The cosmological measurements of tiny anisotropies in Cosmic Microwave Background Radiation (CMBR) by the WMAP and Planck Collaboration [5] suggest that the Universe is

made of 69% dark energy, 27% dark matter, and 4% ordinary matter.

Astrophysical and cosmological data can tell us about the total amount/density of the DM of the Universe. There is still no consensus on what it is composed of and the properties are still unknown. The possibilities of different kinds of baryonic or nonbaryonic DM candidates have been discussed in [22]. The weakly interacting massive particles (WIMPs) are the best viable DM candidates. No evidence of the WIMP has been found from the direct detection experiments such as XENON100 [23], LUX [24, 25], and XENON1T [26]. As these DM-nucleon scattering experiments still have not found any signature in the detector, these experiments have ruled out low mass (10–50 GeV) regions in the parameter space of a Z- and Higgs h-portal DM. Recent LUX-2016 [25] data has also excluded the mass range 65–550 GeV of a h-portal fermionic (it depends on the mixing angle between Higgs and singlet scalar) DM model [27] and scalar DM models [27–29]. It indicates that we may need the multicomponent DM particles to explain the experimental data. We may detect these DMs in the more efficient detector in the future experiments. Multicomponent DM model is needed [30] to explain the Galactic Center gamma ray excess [31] and the colliding galaxy cluster [32–34] simultaneously. Multicomponent DM models have been considered in [35, 36] in various models which also include neutrino, Axion, and supersymmetric particles. Various models with two WIMP candidates could lead to typical signatures at different mass scale and have been studied in [37–58].

We add three right-handed $SU(2)$ singlet fermions and a singlet scalar to the SM. We also impose two Z_2 and Z_2' symmetries. All SM and the first two fermion fields are even under these Z_2 and Z_2' transformations. The Dirac mass terms can be formed using these fermions and the SM neutrinos. We use type I seesaw mechanism to explain the tiny neutrino mass-squared differences and the mixing angles which are observed by the neutrino oscillation experiments. The third Z_2-odd fermion and Z_2'-odd scalar both can serve as viable DM particles in this work. Moreover, the requisite rate of annihilation is ensured by postulating some Z_2 and Z_2' preserving dimension-four and dimension-five operators for the scalar and fermion particles, respectively. The four-point interaction term of the extra fermions and scalar can be obtained from other five-dimensional operators [59]. The interaction term of the third fermion and the scalar allows a larger region of the parameter space than what we would have had with a single DM particle (either fermion or scalar) alone. This interplay brings an enriched DM phenomenology compared to the other models having fermion or scalar DM particle. The region of DM masses 65–550 GeV of a fermionic or scalar Higgs portal DM model is excluded from the present LUX experimental data. In this model, we show that the region with masses 50–550 GeV up to 300 TeV is still allowed by the direct search experiments. Hence, we feel a desirable feature of our model for future study.

The plan of the paper is as follows. In Section 2, we present the theoretical framework of our extended singlet scalar fermionic standard model (ESSFSM). We also discuss the

TABLE 1: The $Z_2 \times Z_2'$ quantum numbers. u represents the *up-type* quarks of the three generations u, c, t and d stand for the *down-type* quarks d, s, b. The charged leptons are denoted by $l = e, \mu, \tau$ with the corresponding left-handed neutrinos ν_l. Φ is the SM Higgs doublet. G^+ (G^0) stand for the charged (neutral) Goldstone boson. L, R stand for left- and right-handed chirality of fermions.

Fields	Charged under $SU(2) \times Z_2 \times Z_2'$ transformation		
	$SU(2)$	Z_2	Z_2'
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	2	1	1
u_R, d_R	1	1	1
$L = \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}$	2	1	1
l_R	1	1	1
$\Phi = \begin{pmatrix} G^+ \\ \dfrac{h + \nu + iG^0}{\sqrt{2}} \end{pmatrix}$	2	1	1
$\nu_{s,1}, \nu_{s,2}$	1	1	1
$\nu_{s,3}$	1	−1	1
S	1	1	−1

diagonalization procedure to get the neutrino mass matrix and the relic density calculation of two dark matter particles. We show the detailed constraints on this model in Section 3. We present our numerical results and show the allowed region in the parameter spaces from the neutrino mass and mixing angle, relic density, and direct detection in Section 4. Finally, we conclude in Section 5.

2. Theoretical Framework of the Model

In this section, we give a description of our model. We add three right-handed neutrinos and a scalar to the SM Lagrangian. These extra particles are singlet under $SU(2)$ transformation. We impose two Z_2 and Z_2' symmetries such that the SM fields and first two right-handed neutrinos are even under these Z_2 and Z_2' transformations. The third right-handed neutrino is odd (even) under Z_2 (Z_2') transformation whereas the scalar field is even (odd) under Z_2 (Z_2') transformation. The $Z_2 \times Z_2'$ quantum numbers of the SM fields and extra right-handed neutrinos and scalar fields are summarized in Table 1. The $Z_2 \times Z_2'$-even neutrinos are free to mix with the usual SM neutrinos and therefore generate the neutrino masses through type I seesaw mechanism. These symmetries prohibited the coupling of an odd number of the third fermion and/or the scalar particle to the SM particles. The part of Lagrangian that is invariant under $SU(2) \times U(1) \times Z_2 \times Z_2'$ transformation is given by

$$\mathcal{L} = \frac{i}{2}\overline{\nu}_{s,a}\slashed{\partial}\nu_{s,a} - \frac{1}{2}\overline{M}_{\nu_{s,a}}\overline{\nu}_{s,a}\nu_{s,a}^c + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{\mu_S}{2}S^2$$
$$- \frac{\lambda_S}{4!}S^4, \tag{1}$$

where summation over a is implied, with $a = 1, 2, 3$ denoting generation indices for the right-handed fermions. c stands for the charge conjugation. The mutual interaction terms of the SM Higgs, left-handed leptons, the extra scalar, and fermions are given by

$$\mathscr{L}_{\text{mix}} = -Y_{\nu,ab}\overline{L}_a\Phi^c\nu_{s,b} - \overline{M}_{\nu_s,mn}\overline{\nu}_{s,m}\nu_{s,n}^c - \frac{\kappa}{2}|\Phi|^2 S^2$$
$$+ \frac{C_{h,mn}}{\Lambda_{h,mn}}|\Phi|^2\overline{\nu}_{s,m}\nu_{s,n}^c + \frac{C_{h,a}}{\Lambda_{h,a}}|\Phi|^2\overline{\nu}_{s,a}\nu_{s,a}^c \qquad (2)$$
$$+ \frac{C_{S,mn}}{\Lambda_{S,mn}}S^2\overline{\nu}_{s,m}\nu_{s,n}^c + \frac{C_{S,a}}{\Lambda_{S,a}}S^2\overline{\nu}_{s,a}\nu_{s,a}^c + \text{h.c.}$$

Φ is the SM Higgs doublet, $\Phi \equiv (G^+, (v + h + iG^0)/\sqrt{2})^T$, where $G^\pm$ and G^0 are the Goldstone bosons, and h is the SM Higgs. Φ^c stands for charge conjugate of Φ. $L \equiv (\nu_l, l)^T$ with $l = e, \mu$ and τ being the left-handed lepton doublet. $b = 1, 2$ does not assume the third index as the third fermion is odd under Z_2-symmetry. The indices $m \neq n = 1, 2$; hence the second term in (2) generates the mixing mass term between two Z_2- and Z_2'-even neutrinos. After electroweak (EW) symmetry breaking, the fourth term, that is, the dimension-five operator also gives an additional mixing mass term. The Higgs to extra neutrinos couplings are also generated from the dimension-five operators (fourth and fifth term in (2)). This will lead to the Higgs boson decay into these extra neutrons. As the Z_2- and Z_2'-even neutrinos are considered to be very heavy, the partial decay width of the Higgs to these neutrinos is zero. As we are allowing these dimension-five operators in the Lagrangian, for completeness, we also add the other dimension-five operators $(C_{S,mn}/\Lambda_{S,mn})S^2\overline{\nu}_{s,m}\nu_{s,n}^c$ and $(C_{S,a}/\Lambda_{S,a})S^2\overline{\nu}_{s,a}\nu_{s,a}^c$, which in turn give more room in the parameter space to maneuver. In this work, we focus on the dominant dimension-five operators related to the neutrino and Higgs portal dark matter physics, that is, those involving at least one Higgs and neglecting other possible operators which are allowed by the SM gauge and $Z_2 \times Z_2'$ symmetries. Λ's are the cut-off scales for the new physics. In our calculation, we assume $\Lambda_{h,a} = \Lambda_{S,a} = \Lambda_{h,mn} = \Lambda_{S,mn} \equiv \Lambda$. $C_{h,a}$, $C_{S,a}$, $C_{h,mn}$, and $C_{S,mn}$ are dimensionless coupling parameters. The cut-off scale Λ and $C_{h,12}$ and the Yukawa couplings $Y_{\nu,ab}$ are important to explain the neutrino oscillation observables, whereas Λ, $C_{h,3}$, $C_{S,3}$, and κ could change the masses and coupling strength of DM particles to the Higgs. In addition, these could alter the self-annihilation interaction probability of the heavier DM particles into the lighter DM particles. Hence, these parameters play a crucial role to calculate the relic density of the DM particles $\nu_{s,3}$ and S. The masses of the DM particles are given by

$$M_{\nu_{s,3}} = \overline{M}_{\nu_{s,3}} - \frac{C_{h,3}}{\Lambda}v^2,$$
$$M_S^2 = \mu_S^2 + \frac{1}{2}\kappa v^2, \qquad (3)$$

and the coupling strength of the DM candidates with the Higgs can be written as

$$h\overline{\nu}_{s,3}\nu_{s,3} : \frac{C_{h,3}}{\Lambda},$$

$$hSS : \frac{\kappa}{2}v. \qquad (4)$$

The parameter $C_{S,3}$ is responsible for the annihilation of $SS \leftrightarrow \overline{\nu}_{s,3}\nu_{s,3}$. This process reduces the number density of the heavier DM till the freeze-out.

It is also important to note that the gauge boson B_μ and/or W_μ^i interactions terms are not present in the kinetic part of the Lagrangian (see (1)). Therefore, this model does not have any extra gauge-boson contribution to the DM-nucleus scattering cross section which is allowing larger region in the parameter space from the direct detection experiments. This is the specialty of the presence of real singlet scalar and fermion in the ESSFSM.

2.1. Diagonalization Procedure of Type I Seesaw Matrix and Nonunitarity of PMNS Matrix. Here, we show the diagonalization procedure [60, 61] of type I seesaw mechanism to generate tiny neutrino mass-squared difference [62, 63]. In this model, 5×5 neutrino mass matrix in the basis (ν_l, ν_s) can be written as

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_{\nu_s} \end{pmatrix}, \qquad (5)$$

where the Dirac mass M_D and Majorana mass M_{ν_s} terms can be written as

$$M_D = \begin{pmatrix} Y_{\nu,11}v & Y_{\nu,12}v \\ Y_{\nu,21}v & Y_{\nu,22}v \\ Y_{\nu,31}v & Y_{\nu,32}v \end{pmatrix},$$
$$M_{\nu_s} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{pmatrix}. \qquad (6)$$

Here, $M_{11} = \overline{M}_{\nu_s,1} - (C_{h,1}/\Lambda)v^2$, $M_{22} = \overline{M}_{\nu_s,2} - (C_{h,2}/\Lambda)v^2$, and $M_{12} = \overline{M}_{\nu_s,12} - (C_{h,12}/\Lambda)v^2$

Using 5×5 unitary matrices [64, 65], one can diagonalize the neutrino mass matrix M_ν in (5). It is given by

$$U^T M_\nu U = M_\nu^{\text{diag}}, \qquad (7)$$

where $M_\nu^{\text{diag}} = \text{diag}(m_i, M_j)$ with mass eigenvalues m_i ($i = 1, 2, 3$) for three light neutrinos and M_j ($j = 1, 2$) for two heavy neutrinos, respectively. In this calculation, we have two nonzero mass eigenstates of light neutrinos. We consider m_1 to be zero. In the limit $M_D^2 \ll M_{\nu_s}^2$, the matrix U can be expressed as follows [61]:

$$U = WT = \begin{pmatrix} U_L & V \\ S & U_H \end{pmatrix}$$
$$= \begin{pmatrix} \left(1 - \frac{1}{2}\epsilon\right)U_\nu & M_D^*\left(M_{\nu_s}^{-1}\right)^* U_R \\ -M_{\nu_s}^{-1}M_D^T U_\nu & \left(1 - \frac{1}{2}\epsilon'\right)U_R \end{pmatrix}, \qquad (8)$$

where U_L, V, S and U_H are $3 \times 3, 2 \times 3, 3 \times 2$ and 2×2 matrices, respectively, which are not unitary. The unitary W matrix which brings the full 5×5 neutrino matrix in the block diagonal forms as

$$W^T \begin{pmatrix} 0 & \widehat{M}_D \\ M_D^T & M_{\nu_s} \end{pmatrix} W = \begin{pmatrix} m_{\text{light}} & 0 \\ 0 & M_{\text{heavy}} \end{pmatrix}. \qquad (9)$$

Another unitary matrix $T = \text{diag}(U_\nu, U_R)$ matrix again diagonalizes the mass matrices in the light and heavy sectors are appearing in the upper and lower block of the block diagonal matrix, respectively. In the above-stated limit, one can then write the light neutrino mass matrix to the leading order as

$$m_{\text{light}} = M_D M_{\nu_s}^{-1} M_D^T. \qquad (10)$$

In (8), U_L corresponds to the PMNS matrix which acquires a nonunitary correction $(1 - \epsilon/2)$ due to the presence of heavy neutrinos. The characterizations of nonunitarity are denoted by the notations ϵ and ϵ'. These are given by the following [60]:

$$\epsilon = M_D^* M_{\nu_s}^{-1*} M_{\nu_s}^{-1} M_D^T,$$
$$\epsilon' = M_{\nu_s}^{-1} M_D^T M_D^* M_{\nu_s}^{-1*}. \qquad (11)$$

2.2. Relic Density Calculation of the Two-Component Dark Matter. In order to calculate the relic abundance of two-component DM in the present formalism, we need to solve the relevant coupled Boltzmann equations [66]:

$$\frac{dn_{\nu_{s,3}}}{dt} + 3H n_{\nu_{s,3}}$$
$$= - \langle \sigma v \rangle_{\nu_{s,3} \nu_{s,3} \to XX} \left(n_{\nu_{s,3}}^2 - n_{\nu_{s,3}\text{eq}}^2 \right)$$
$$\quad - \langle \sigma v \rangle_{\nu_{s,3} \nu_{s,3} \to SS} \left(n_{\nu_{s,3}}^2 - \frac{n_{\nu_{s,3}\text{eq}}^2}{n_{S_{\text{eq}}}^2} n_S^2 \right),$$

$$\frac{dn_S}{dt} + 3H n_S$$
$$= - \langle \sigma v \rangle_{SS \to XX} \left(n_S^2 - n_{S_{\text{eq}}}^2 \right)$$
$$\quad - \langle \sigma v \rangle_{SS \to \nu_{s,3} \nu_{s,3}} \left(n_S^2 - \frac{n_{S_{\text{eq}}}^2}{n_{\nu_{s,3}\text{eq}}^2} n_{\nu_{s,3}}^2 \right), \qquad (12)$$

where Z_2-even (SM, $\nu_{s,2}$ and $\nu_{s,2}$) particles are denoted by X. In addition, the heavier X can decay into lighter particles. $\langle \sigma v \rangle$ is the average effective annihilation cross sections of the DM candidates which include all $n \geq 2$-body final state particles. The first term on the right-hand side of (12) indicates the contribution of annihilation to SM particles whereas the second term in both equations takes care of the contribution of the self-scattering of DM particles. The contributions from the processes $\nu_{s,3} S \to \nu_{s,3} S$ are zero as it does not alter the number density. In the very early Universe, both of the DM candidates are in thermal and chemical equilibrium. In the

nonrelativistic case, if the temperature T of the Universe is less than the DM masses, then the equilibrium number density takes the form $n_{\text{DM eq}} = (M_{\text{DM}} T / 2\pi)^{3/2} \exp(-M_{\text{DM}}/T)$. As the temperature was falling down, some species are decoupled and contributing to the relic density. The heavier DM candidate particle decouples earlier than the lighter one. In the present Universe, they both were frozen out and giving a partial contribution in the total relic abundance Ω_{tot}. If the individual contributions of the fermion and scalar are $\Omega_{\nu_{s,3}}$ and Ω_S, then the total relic abundance Ω_{tot} can be written as

$$\Omega_{\text{DM}} = \Omega_{\nu_{s,3}} + \Omega_S, \qquad (13)$$

where $\Omega_{\nu_{s,3}} = (M_{\nu_{s,3}}/\rho_c) n_{\nu_{s,3}}(T_0)$ and $\Omega_{\nu_{s,3}} = (M_S/\rho_c) n_S(T_0)$. $\rho_c \sim 1.05 \times 10^{-5} h^2 \, \text{GeV cm}^{-3}$ stands for the critical density of the present Universe; $h = 0.72$ is the Hubble parameter. $n(T_0)$ is the number density of the DM at temperature T_0 today.

One can note that if the masses of the DM particles are degenerate, then the Boltzmann equations (12) become decoupled; that is, self-scattering cross sections of the process $\nu_{s,3} \nu_{s,3} \leftrightarrow SS$ are very small compared to the self-annihilation cross section of the DM. These equations describe the evolution of each DM independently. In our calculation, we use the `micrOMEGAs` [66] and solve the above coupled Boltzmann equations to calculate the individual number density of the DM particles in the present Universe.

3. Constraints on the Model

The parameter spaces of this model are constrained from various theoretical considerations like absolute vacuum stability, perturbation, and unitarity of the scattering matrix. The absolute stability of the Higgs potential demands that the scalar potential should not approach to negative infinity along any direction of the field space at large field values. The required conditions are $\lambda > 0$, $\lambda_S > 0$, and $\kappa > -\sqrt{2\lambda\lambda_s}/\sqrt{2}$, where λ is the Higgs quartic coupling [29]. Lagrangian of our model remains perturbative [67, 68] for $|\lambda| \leq 4\pi/3$, $|\kappa| \leq 8\pi$, $|\lambda_S(\Lambda)| \leq 8\pi, C_{h,a} \leq 8\pi$, and $C_{S,a} \leq 8\pi$. The parameters of the scalar part of Lagrangian (see (1) and (2)) of this model are constrained by the unitarity of the scattering matrix (S-matrix). One can obtain the S-matrix by using various scalar-scalar, gauge boson-gauge boson, and scalar-gauge boson scattering amplitudes. We use the equivalence theorem [69–71] to reproduce the S-matrix for this model [68]. The unitary bounds demand that the eigenvalues of this matrix should be less than 8π which imply $\lambda \leq 8\pi$ and $|12\lambda + \lambda_S \pm \sqrt{16\kappa^2 + (-12\lambda + \lambda_S)^2}| \leq 32\pi$.

The observed neutrino mass-squared differences and mixing angles by the neutrino oscillation experiments put stringent constraints on the parameter space of this model. The Higgs signal strength and the decay width measured by the LHC, the relic density, and direct-indirect searches of DM all alone restrict the allowed parameter space considerably. We discuss these in the following.

3.1. Bounds from the Neutral Fermion Mass and Mixing Angles. The global analysis of neutrino oscillation measurements

provides the neutrino oscillation parameters for both normal and inverted hierarchies scenario. These can be found in [62, 63]. The measurements of the electroweak precision observables along with other experimental data put severe constraints on the light neutrino mixing matrix U_L. The detailed analysis has been given in Refs [72, 73].

The L3 collaboration at the LEP had analyzed the decay channels $N \rightarrow e^{\pm} W^{\mp}$ to find the evidence of the heavy neutrino. No signature had been found for the mass range in between 80 GeV (with $|V_{\alpha i}|^2 \leq 2 \times 10^{-5}$) and 205 GeV (with $|V_{\alpha i}|^2 \leq 1$) [74]. V is the light-heavy mixing matrix, given in (8). This puts a lower bound on the mass of the heavy neutrino and the mixing matrix elements $V_{\alpha i}$. $|V_{\alpha i}|^2 \gtrsim 10^{-5}$ and $3 < M_{1,2} < M_Z$ regions have also been ruled out from the invisible decay width of the Z-boson [75–77].

The experimental data [78] $\mathrm{Br}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ of the flavor changing decay processes has restricted the arbitrary Yukawa coupling Y_ν. In this model, the branching ratio can be written as follows [79]:

$$\mathrm{Br}\left(\mu \longrightarrow e\gamma\right) = \frac{3\alpha}{8\pi} \left| V_{ei} V_{i\mu}^\dagger f\left(x\right) \right|^2, \qquad (14)$$

where $x = (M_i^2/M_W^2)$, $i = 1, 2$, stands for the mass of heavy neutrinos and $f(x)$ is the slowly varying function can be found in [79].

3.2. Bounds from the Higgs Signal Strength at the LHC.
The dominant contribution of the Higgs h-production cross section is coming through the gluon fusion. In this work, the Higgs to diphoton signal strength $\mu_{\gamma\gamma}$ can be written as

$$\mu_{\gamma\gamma} \simeq \frac{\sigma\left(gg \rightarrow h \rightarrow \gamma\gamma\right)_{\mathrm{ESSFSM}}}{\sigma\left(gg \rightarrow h \rightarrow \gamma\gamma\right)_{\mathrm{SM}}}$$
$$= \frac{\sigma\left(gg \rightarrow h\right)_{\mathrm{ESSFSM}}}{\sigma\left(gg \rightarrow h\right)_{\mathrm{SM}}} \frac{\mathrm{Br}\left(h \rightarrow \gamma\gamma\right)_{\mathrm{ESSFSM}}}{\mathrm{Br}\left(h \rightarrow \gamma\gamma\right)_{\mathrm{SM}}}. \qquad (15)$$

The production cross section of h is the same as in the SM. Then $\mu_{\gamma\gamma}$ can be written as

$$\mu_{\gamma\gamma} = \frac{\Gamma_{h,\mathrm{SM}}^{\mathrm{total}}}{\Gamma_{h,\mathrm{ESSFM}}^{\mathrm{total}}}, \quad \mathrm{as} \ \frac{\Gamma_h^{\mathrm{total}}}{M_h} \longrightarrow 0. \qquad (16)$$

As we do not have any extra charged particle, the decay width $\Gamma(h \rightarrow \gamma\gamma)$ is the same as in the SM. If the extra particles (scalar and fermions) have the mass less than half of the Higgs mass $M_h/2$, then the diphoton signal strength could be changed due to the invisible decay of the Higgs boson. Using the global fit analysis [80] that such an invisible branching ratio is less than ~20%, so the decay width in (16) provides a suppression of about ~80–100 percent. The present combined value of $\mu_{\gamma\gamma}$ by the ATLAS and CMS collaborations is $1.14^{+0.19}_{-0.18}$ [81]. As the partial decay width of the Higgs to the heavy Z_2- and Z_2'-even neutrinos is zero, it cannot alter $\mu_{\gamma\gamma}$. We also check that the mass region $M_{\mathrm{DM}} < 55$ GeV of the Z_2'-odd scalar and Z_2-odd neutrino DM along with $|\kappa| \gtrsim 0.004$ and/or $|C_{h,3}| \gtrsim 0.2$ is excluded at 2σ.

3.3. Relic Density and Direct Search Limits.
The relic density of DM all alone restricts the allowed parameter space. The parameter space of this model should also satisfy the combined WMAP and Planck [82] imposed dark matter relic density constraint $\Omega_{\mathrm{tot}} h^2 = 0.1198 \pm 0.0026$. In our calculation, we use the `micrOMEGAs` [66] to calculate the total relic density of the two DM particles. In this model, we find the correct relic density for the dark matter particles mass $M_{\mathrm{DM}} < 55$ GeV. However, these regions in the parameter spaces are ruled out from the invisible Higgs decay width and direct search data. In the following, we discuss the detailed constraints from direct detection of two-component dark matter particles.

The WIMPs, in particular, those that have nonvanishing weak interactions with the SM and therefore can be tested. They are actively being searched for in the direct detection experiments which look for their nuclear scatterings in the deep underground detectors. If the DM scatters from atomic nucleus, then it leaves their signature in form of a recoiled nucleus. However, no confirmed detection of the DM in the experimental laboratory has been made so far. If a discovery is within the reach of a near-future direct detection experiment, then these experiments will be able to constrain the WIMP properties such as its mass, DM-nucleus scattering cross section, and possibly spin.

As we have two-component DM, it is very difficult to distinguish these DM particles in the direct detection experiment. The local number density of the DM particles in the solar neighborhood is important in determining the total number of event rate in the experiment. It is not entirely straightforward to determine which component dominates the event rate. There have been only a few works regarding the direct detection of multicomponent DM [83–85]. The signal rate generated from two-component DM in the detector is different compared to a single-component DM and it completely depends on the DM masses and local densities in the solar neighborhood. The particle masses will determine their individual rates (see section 3.2 of [85]) that can distinguish one- or two-component DM if the DM particles have different masses.

Presently, nonobservation of DM in the direct detection experiments such as XENON100 [23], LUX [24, 25], and XENON1T [26] sets a limit on WIMP-nucleon scattering cross section for given DM masses. The most stringent bound is set by the XENON1T [26] and LUX 2016 [25] exclusion data. The region above the green line in Figure 2 is excluded. We translate the LUX exclusion data into some allowed or excluded zones in the parameter spaces of our model comprising $C_{h,3}$, $M_{\nu_{s,3}}$, κ, M_S and $C_{S,3}$. In this model, the Feynman diagrams for the scattering of DM particles $\nu_{s,3}, S$ with the nuclei are shown in Figure 1. In the limit $M_{\mathrm{DM}}(M_{\nu_{s,3}}, M_S) \gg M_N$, the fermion-nucleon and scalar-nucleon scattering cross sections are roughly given by

$$\sigma_{\nu_{s,3}, N} = X_N \left(\frac{C_{h,3}}{\Lambda M_{\nu_{s,3}}}\right)^2,$$
$$\sigma_{S,N} = \frac{X_N}{2} \left(\frac{\kappa}{M_S}\right)^2, \qquad (17)$$
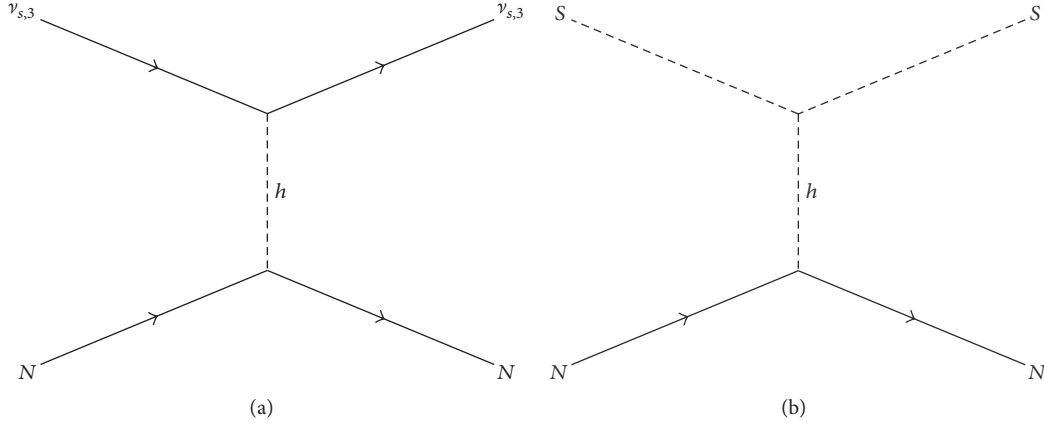
FIGURE 1: (a) Lowest order Feynman diagram for singlet neutrino-nucleus elastic scattering via the Higgs mediation. (b) A similar diagram for the singlet scalar-nucleus elastic scattering.

where $X_N = (m_r m_N f / \sqrt{\pi} M_h^2)^2$ and $f \approx 0.3$ is the form factor of the nucleus. m_r represents the reduced mass of the nucleus and the scattered DM particle.

Using (17), we calculate the DM-nucleon cross sections for the two dark matter components of different mass. The region in the parameter space for which DM-nucleon cross section falls above the green line in Figure 2 is ruled out by the recent LUX-2016 [25] exclusion data. The region above the purple line is ruled out by the recent XENON-2017 [26] data.

4. Numerical Results

We explain the neutrino mass using type I seesaw mechanism. We show that our results are compatible with the various constraints such as the charged lepton flavor violating decay $\mu \rightarrow e\gamma$. In addition, the extra Z_2-odd fermion and the Z_2'-odd scalar both can serve as viable DM particles producing the relic density in the right ballpark. We show that the regions in the parameter space are consistent with the Planck/WMAP as well as LUX-2016 and XENON-2017 data. In this study, we use `FeynRules` [86] along with `micrOMEGAs` [66] to compute the relic density of the DM candidates $\nu_{s,3}$ and S. We will discuss these in the following.

4.1. Neutrino Oscillation Parameters. We obtain tiny neutrino mass through type I seesaw mechanism. We use the input parameters such as the new Yukawa couplings $Y_{\nu,ij}$ ($i = 1, 2, 3$ and $j = 1, 2$), dimensionless couplings $C_{h,1}$, $C_{h,2}$, $C_{h,12}$, and the mass terms $\overline{M}_{\nu_s,1}$, $\overline{M}_{\nu_s,2}$, and $\overline{M}_{\nu_s,12}$. In our calculation, we assume cut-off scale for the new physics is $\Lambda = 10$ TeV. In order to explain successful leptogenesis [87, 88], we need complex Yukawa coupling to have nonzero CP-violation. The detailed discussion can be found in [61]. The presence of the extra Majorana neutrinos will allow for neutrinoless double β-decay [12]. In this work, we use the nonzero and real Yukawa couplings $Y_{\nu,12} = Y_{\nu,23}$ ($\equiv y_\nu$). Other Yukawa couplings are taken to zero. We chose the values of parameters $\overline{M}_{\nu_s,12}$ and $C_{h,12}$ such that the off-diagonal components of the

heavy mass matrix M_{ν_s} become zero (see (6)). We consider three heavy neutrino masses $\mathcal{O}(10^{11})$ GeV, $\mathcal{O}(10^5)$ GeV, and $\mathcal{O}(10^3)$ GeV and the corresponding three different Yukawa couplings y_ν to obtain tiny the neutrino masses. We present these benchmark points and the corresponding low-energy variables in Table 2. These variables are consistent with the experimental data. As the cut-off scale for the new physics Λ is very large, the dimensionless couplings C_h (within perturbative limit) could not alter the neutrino mass considerably.
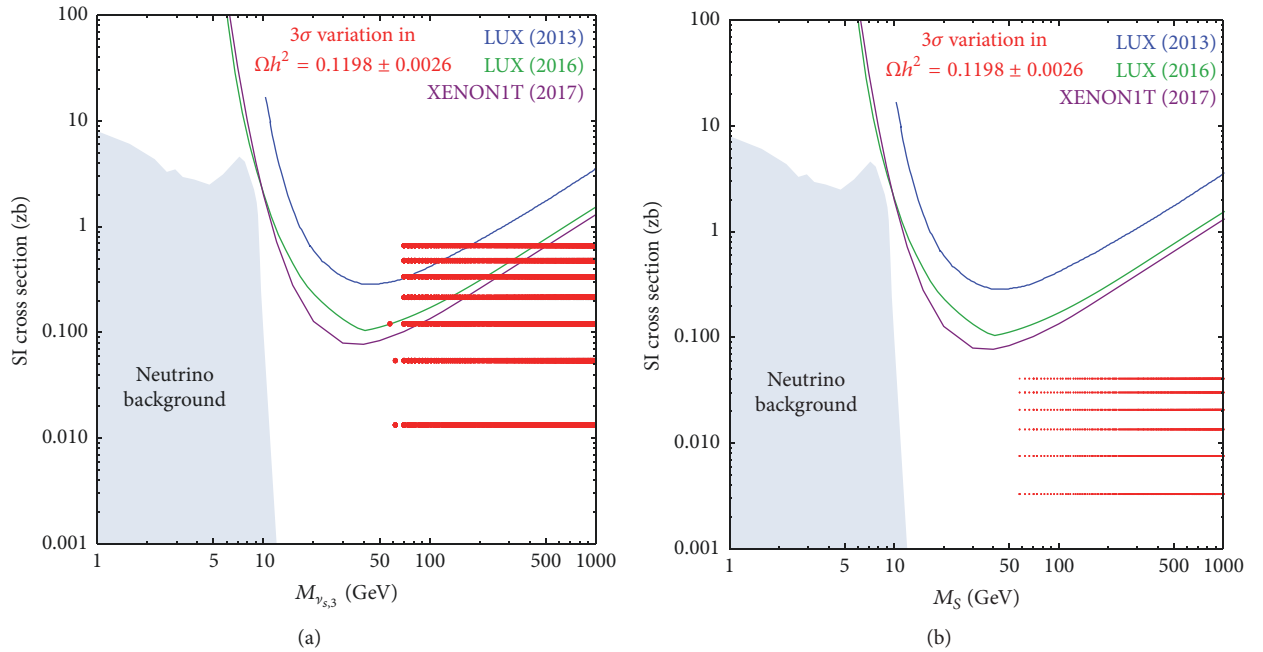
4.2. New Regions in the DM Parameter Space. We have seen that the region in the parameter space $M_{\text{DM}} < \mathcal{O}(500)$ GeV of a single Higgs portal WIMP DM particle is ruled out by the recent LUX experiment. Hence, it becomes important to show that these regions in the parameter space are still alive in the ESSFSM. In Table 3, we present five benchmark points for this model which are producing right relic density and allowed by the recent nonobservation of DM-nucleon scattering in the LUX experiment. The DM mass regions below the half of the Higgs mass are also consistent with the Higgs invisible decay width [80]. If the mass difference between the fermionic and scalar DM particles is very large, then it is expected that lighter one will dominate over the heavier one in contributing to the relic density. For $M_{\nu_{s,3}} \simeq M_S$ and tiny interaction coupling $C_{S,3}$, the contribution of these DM particles is nearly equal to the total relic density, whereas the interaction coupling $C_{S,3} \sim \mathbf{O}(1)$ and a huge mass difference in the DM particles with particular Higgs portal couplings κ and $C_{h,3}$ can produce equal relic density in the Universe. For example, see benchmark points I–IV. The lighter DM mass near 60 GeV will always dominate over the heavier one because the contribution of self-annihilation processes DM, DM $\rightarrow b\bar{b}$ into the relic density is larger than the other processes. The other processes can dominate over the DM, DM $\rightarrow b\bar{b}$ process for the choice of the large Higgs portal coupling κ. In this case, the relic density and the direct detection data restrict such a choice of κ.

TABLE 2: Three lists of benchmark points used in our analysis. Using these BPs, we have obtained the outputs for our model which are satisfying all the low energy constraints.

Parameters	Benchmark points for Z_2- and Z_2'-even fermions		
	BM-I	BM-II	BM-III
M_{11} GeV	1.2×10^{11}	7.1×10^5	6.9×10^3
$C_{h,1}$	0.1	0.01	0
M_{22} GeV	1.4×10^{12}	2.36×10^5	2.41×10^3
$C_{h,2}$	0.1	0.01	0
M_{12} GeV	0	0	0
y_ν	0.01	10^{-5}	10^{-6}
Outputs	Corresponding low-energy variables		
$\Delta m_{21}^2/10^{-5}$ eV^2	7.5001	7.2909	7.7197
$\Delta m_{31}^2/10^{-3}$ eV^2	2.55234	2.63959	2.5312
θ_{12}	0.5883	0.5774	0.5720
θ_{23}	0.7953	0.7854	0.7803
θ_{13}	0.1476	0.1473	0.1469
δ_{PMNS} rad	10^{-5}	10^{-4}	10^{-3}
α rad	1.7	1.8	1.9
m_i eV	0, 0.0087, 0.0505	0, 0.0085, 0.0514	0, 0.0088, 0.0505
Br($\mu \to e\gamma$)	3.0×10^{-48}	1.9×10^{-37}	1.69×10^{-33}

TABLE 3: Lists of benchmark points used in our analysis. Using these BPs we obtain the relic density in the right ballpark allowed by LUX-2016 direct detection data.

Benchmark points	Parameters					Relic density Ωh^2	Percentage of DM		DM-N cross section in [zb]	
	$M_{\nu_{s,3}}$ GeV	$C_{h,3}$	M_S GeV	κ	$C_{S,3}$		Fermion	Scalar	Fermion	Scalar
BP-I	260	0.05	59	0.0015	0.1	0.1271	39.12	61.88	0.33	0.0054
BP-II	130	0.01	60	0.001	0.1	0.1263	40.68	59.32	0.013	0.0023
BP-III	86	−0.01	59.8	0.0012	0.1	0.1129	53.10	46.90	0.013	0.0033
BP-IV	62	−0.01	60.9	0.0016	0.1	0.1156	69.76	30.24	0.013	0.0058
BP-V	59	0.02	250	0.0025	0.1	0.1201	99.6	0.4	0.053	0.0008

FIGURE 2: WIMP-nucleon cross section versus DM mass keeping $C_{S,3} = 0.1$. The gray region indicates the neutrino background. Note that each plot contains only 10^7 data (red) points. Larger data points can fill the gap between the red bands.
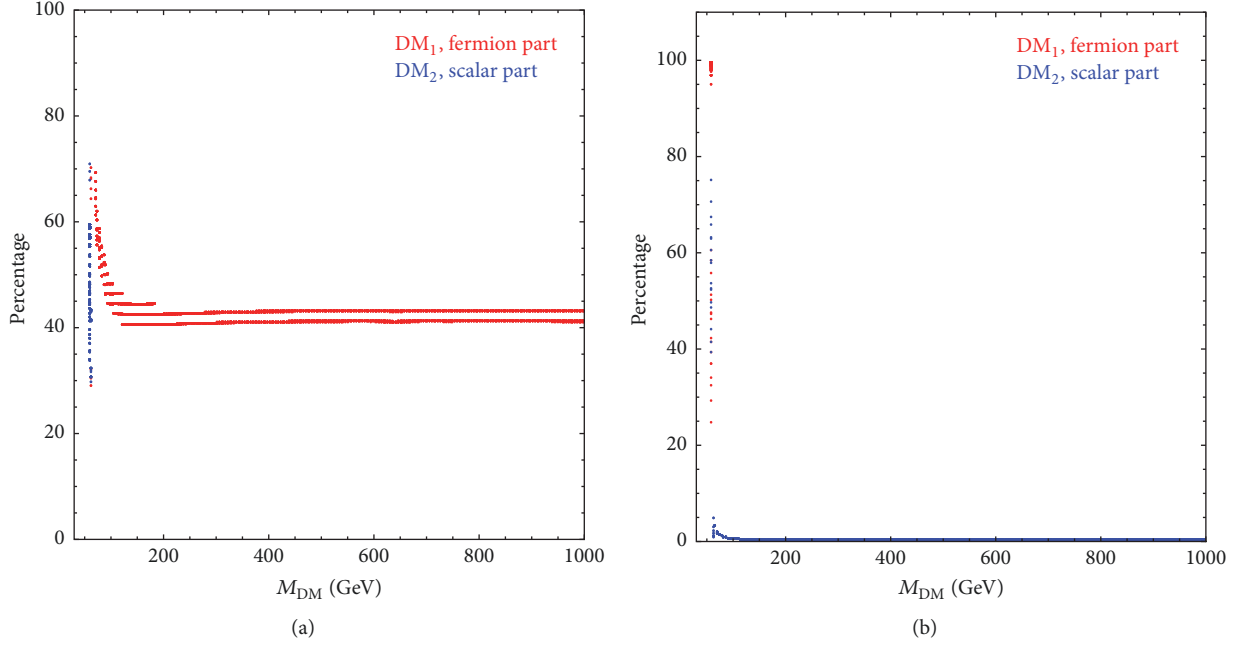
FIGURE 3: Percentage of DM contributing to the total relic density. Red points correspond to the fermionic DM contributions whereas blue points correspond to the singlet scalar.

In order to find the favored regions in the parameter space which satisfies DM relic density constraints and the recent LUX direct detection data, in Figure 2, we present two contour plots of relic density Ωh^2 in the DM-nucleon cross section versus mass plane. The red points are consistent with the relic density $\Omega h^2 = 0.1198 \pm 0.0026$ within 3σ. We vary $C_{h,3}$ from -0.7 to 0.7 and κ from 0 to 0.75 to obtain Figure 2. We also fix the coupling $C_{S,3} = 0.1$ in these plots.

In Figure 2(a), we vary the scalar DM mass between 55 GeV and 65 GeV and the fermion DM mass between 40 and 1000 GeV. In Figure 2(b), we take the variation of the fermionic DM mass between 55 GeV and 65 GeV and the scalar mass between 40 and 1000 GeV. We find that a large region in the parameter space satisfies the bound on WIMP-nucleon cross section as imposed by the recent LUX-2016 and XENON-2017 experimental data. We find that the scalar DM mass $M_S \sim 60$ Gev provides the dominant contributions in the relic density. The contribution decreases with M_S. However, we need this scalar part to achieve the relic density as observed by the WMAP/Planck. In the second case, the fermionic contribution remains the same ($\sim 50\%$) in the region $55 \lesssim M_S \lesssim 65$ GeV. We show these variations of the DM contribution in Figure 3 with the DM mass. The red points indicate the fermionic contribution whereas blue points stand for the scalar contribution to the correct relic density ($\Omega h^2 = 0.1198 \pm 0.0026$) within 3σ.

5. Conclusion

In this paper, using two right-handed singlet fermions, we have explained the neutrino mass through type I seesaw mechanism. We have chosen three representative "benchmark points" of three different Majorana mass parameter

spaces ($\sim 10^3$, 10^6, and 10^{12}) and particular structure of the Yukawa couplings matrix, that is, the Dirac mass matrix to explain the neutrino mass-squared differences as observed by the neutrino experiments. We have also calculated the PMNS mixing angles and the other low-energy variables, that is, nonunitary constraints on the PMNS matrix and LFV constraints from $\mu \rightarrow e\gamma$. The combinations of the new Yukawa couplings and the heavy neutrino mass satisfied the neutrino mass and mixing angles constraints [89].

In the presence of Z_2 and Z_2' symmetries, we have also analyzed the two-component Higgs portal self-annihilating dark matter particles. The regions of mass 65–550 GeV of a Higgs portal fermionic or scalar dark matter models are excluded by the recent LUX experiment. In this model, we have shown that the regions of the parameter space with two-component dark matter particles are still allowed from direct search experiment and the WMAP/Planck data. For different fermionic Higgs portal coupling $C_{h,3}$ and fermion dark matter mass, we have obtained viable scalar dark matter mass between 50 GeV and ~ 300 TeV. We have also obtained the similar region of fermionic dark matter mass for different scalar Higgs portal coupling κ. The unitary bounds are violated the dark matter mass above 300 TeV [90]. Here, we do not intend to show that all the parameter spaces satisfy the experimental results. Rather, in the framework of our model, we have wanted to use the advantage of a two-component dark matter which has a large region of parameter spaces satisfying the constraint of various dark matter experiments.

The model ESSFSM is considered here to present the minimal seesaw mechanism and two-component dark matters in terms of particles content. This model can explain the observed tiny neutrino mass-squared differences and the mixing angles in oscillation experiments. The regions in the

parameter space are also consistent with the relic density of dark matter observed by the Planck, WMAP experiments, and the recent null results of the WIMPs dark matter from the direct search LUX-2016 and XENON-2017 experiments.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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